Decay of Solar Active Regions

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ABSTRACT

We examine the record of sunspot group areas observed over a period of 100 years to determine the rate of decay of solar active regions. We exclude observations of groups when they are more than 60° in longitude from the central meridian and only include data when at least three days of observations are available following the date of maximum area for a spot group's disk passage. This leaves data for some 24,000 observations of active region decay. We find that the decay rate is a constant 20 μHem day^{-1} for spots smaller than about 200 μHem (about the size of a supergranule). This decay rate increases linearly to about 90μHem day^{-1} for spots with areas of 1000 μHem. We find no evidence for significant variations in active region decay from one solar cycle to another. However, we do find that the decay rate is slower at lower latitudes. This gives a slower decay rate during the declining phase of sunspot cycles.

Subject headings: Sun:Sunspots — Sun:Active Regions

1. Introduction

The areas of the solar photosphere containing sunspots are known as active regions, as these are the centers of solar activity ranging from compact flares to many of the large-scale coronal mass ejections. They are believed to be the locations where magnetic flux bundles erupt from below the photosphere due to magnetic buoyancy. They emerge in a time scale of hours to days and survive for days to weeks. These objects should have a lifetime of about 300 years, considering their size and the photospheric conductivity, if the decay is purely ohmic dissipation (Cowling 1946). On the other hand, their dynamical time scale, which is the time taken for Alfvén or magneto-acoustic waves to cross the active region, is only about an hour. Further, Parker (1975) suggested that sunspots are intrinsically unstable due to an interchange or fluting instability caused by magnetic tension in the field which fans out with height as the surrounding pressure decreases. However, for sufficiently large magnetic flux concentrations the added buoyancy can counteract this instability (Meyer, Schmidt, & Weiss 1977). Consequently, several alternative mechanisms have been suggested to play significant roles in active region decay. These mechanisms include turbulent diffusion (Krause & Rüdiger 1975), turbulent erosion (Petrovay & van Driel-Gesztelyi 1997), and submergence (Howard 1992a; Kálmán 2001) .

An active region typically consists of one or more compact spots of one magnetic polarity leading (in the direction of solar rotation) a more scattered group of smaller spots with the opposite polarity. This configuration is believed to be a direct consequence of the effect of the Coriolis force on the rising magnetic flux bundle (Fan, Fisher & DeLuca 1993; Fan, Fisher & McClymont 1994). The decay of these two types of spots (leading and following) is seen to be different (Bumba 1963; Martínez Pillet 2002). The decay of an active region is some combination of these two. Bumba (1963) also noted distinct differences between the decay of recurrent spot groups (long-lived regions that are seen on successive solar rotations) and non-recurrent spot groups. As might be expected, the long-lived regions exhibited significantly smaller decay rates.

One of the important questions regarding the decay of active regions concerns the relationship between decay rate and area. Bumba suggested that there are two different decay rates – a slow one for large stable spots and a fast one for small spots – both independent of area. A decay rate independent of area would indicate a diffusion process (Stix 2002) in which the diffusion would work to remove flux over the entire spot area. In more recent studies the decay rates were found to depend on the size but with different functional forms. Moreno-Insertis & Vázquez (1988) and Petrovay & van Driel-Gesztelyi (1997) find decay rates that vary like the square-root of the area which suggests erosion from the edges of the spots. On the other hand Chapman et al. (2003) find rates that are directly proportional to the area.

Recent sunspot models suggest that the highly inclined penumbral fields surrounding sunspot unbrae are pulled down by the granular convection (Thomas et al. 2002). This process would give a decay rate that would depend on the length of the circumference (or square-root of the area) rather than area itself. In this paper, we revisit this problem by analyzing a large database of daily sunspot observations.

2. Data and Sunspot Group Selection

The Royal Greenwich Observatory (RGO) compiled daily observations of sunspot group positions and areas from 1874 to 1976. We have examined this data to extract sunspot group histories – the daily total corrected (for projection effects) sunspot area for the disk passage of each sunspot group. Since the sunspot area corrections are large for observation near the limb, we only include observations for spot groups within 60° of longitude from the central meridian. We also exclude groups with corrected areas less than 35 millionths of a solar hemisphere (μHem). The projected sizes of these smaller spots place them near the limit of spatial resolution thus making the area measurements more uncertain.

Our primary interest is in the decay rate of active regions. For each sunspot group history we determine when the group reaches its maximum size. We then include only those observations that follow the time of maximum and further limit the data to those with at least three consecutive days of data following the maximum. The decay rate, Γ, for day n when the group has area A is then determined by finding the difference in the area between the day before and the day after such that

$$\Gamma(A(n)) = [A(n-1) - A(n+1)]/2 \ \mu\mathrm{Hem\ day}^{-1} \tag{1}$$

These selection criteria eliminate many groups that are either too small or reach maximum size too late in their disk passage. On the other hand, the criteria often include multiple decay rate measurements for a single group.

An example of the measurement of a decaying active region (NOAA AR9415) is shown in Fig. 1 to illustrate the process. For this particular active region we obtain four measurements of the decay rate: 150 μHem day^{-1} at an area of 760 μHem on April 9th, 105 μHem day^{-1} at an area of 490 μHem on April 10th, -15 μHem day^{-1} at an area of 550 μHem on April 11th, and 80 μHem day^{-1} at an area of 520 μHem on April 12th. Data prior to April 8th are excluded because they come before the decay phase starts. Data after April 13th are excluded because they are obtained at central meridian distances greater than 60°. Note that while this region was in its decay phase it had a small negative decay rate (growth) on one day.

3. Results

We obtain over 24,000 measurements of active region decay rates using data from 1874 to 1976. We bin the measurements according to area with 23 bins 20 μHem wide from 40 to 500 μHem and another 20 bins 50 μHem wide from 500 to 1500 μHem. A histogram showing the distribution of measurements for the bin with areas between 140 and 160 μHem is shown in Fig. 2. The distribution is broad and skewed toward higher decay rates. While the mean decay rate (20.3 μHem day^{-1}) is not too different from the median values (17.5 Hem day-1), the mode is somewhat lower (12.5 μHem day^{-1}).

The mean decay rates and their standard errors for each of the 43 sunspot area bins are shown in Fig. 3. Small regions, those with areas less than $\sim$ 200 μHem, have a decay rate of about 20 μHem day^{-1} that is independent of area itself. (Note that fully half of the decay rate measurements are for these small regions.) Larger regions have decay rates that increase linearly with area up to areas of about 1000 μHem. The largest regions have decay rates that tend to fall below this linear relationship.

We have examined active region decay for each of the sunspot cycles covered by the RGO data - cycles 12 through 20. Without exception we find similar behavior - a constant decay rate for small regions and linearly increasing decay rates for larger regions. Figure 4 shows the error ellipses for the two key parameters ("intercept" - the average for the flat toe of the curve – and slope) for each sunspot cycle along with the error ellipse for the full dataset. While there may be a slight tendency for large amplitude cycles to have higher intercepts, this tendency does not appear to be significant.

We have also separated the data by sunspot cycle phase. In one pairing we examine the minimum and maximum phases in which the data is separated at the midpoint in time between adjacent minima and maxima. This pairing gives a large sample from the maximum phase and a much smaller sample from the minimum phase In another pairing we examine the rising and falling phases. The rising phases begin with the appearance of the first new cycle spots near the time of sunspot cycle minimum and end at smoothed sunspot cycle maximum. Likewise, the falling phases begin at the time of smoothed sunspot cycle maximum and end with the last appearance of old cycle spots near the time of the next cycle minimum. This second pairing gives two sample of nearly equal size.

Fig. 5 shows the decay rate parameter error ellipses for these different phases of the solar activity cycle. The maximum phase has a higher intercept but lower slope than the minimum phase. These are somewhat offsetting and the error ellipses do overlap. On the other hand, the rising phase has both a higher intercept and a higher slope than the falling phase and the error ellipses do not overlap. This indicates that, in general, active regions decay more slowly during the falling phase of each sunspot cycle. This appears to be a latitude effect. At the start of each cycle the spots are predominantly at high latitudes while they are near the equator late in the cycle. We check for a latitude dependence by separated the data into two nearly equal parts by the latitude of the regions - high latitudes ($> 15°$) and low latitudes ($\leq 15°$) - and find even more extreme differences. Low latitude spots decay more slowly than high latitude spots.

4. Discussion

We find an interesting relationship between active region decay and the size of the active region itself. Active regions smaller than about 200 μHem decay at a rate of about 20 μHem day^{-1}. This decay rate is independent of area for these smaller spots and this is evident even when the data is separated by sunspot cycle, sunspot cycle phase, and latitude. Larger regions decay at rates that increase linearly with region area up to areas of about 1000 μHem. The largest spots have decay rates that fall somewhat below this linear relationship.

The constant decay rate at the toe of the decay rate vs. area curve (Fig. 3) suggests a purely diffusive process. The decay rate for normal "Fickian" diffusion of a passive scalar quantity is independent of area. Consider the diffusion in two dimensions of a point source. The concentration, $C(r,t)$, is governed by the diffusion equation

$$\frac{\partial C}{\partial t} = \eta \nabla_H^2 C = \frac{\eta}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right) \tag{2}$$

where η is the diffusivity and r is the radial distance from the origin of the point source. Starting with a delta function source of intensity F, the concentration is given by

$$C(r,t) = \frac{F}{4\pi\eta t}\exp\left(-\frac{r^2}{4\eta t}\right) \tag{3}$$

If we chose a concentration level, C_0, the circle containing higher concentration levels grows and then decays. The area contained within its boundary is given by

$$A\left(t\right) = -4\pi\eta t \ln\left(4\pi t\eta\frac{C_0}{F}\right) \tag{4}$$

During the decay phase the decay rate becomes

$$\Gamma = -4\pi\eta \tag{5}$$

a rate that is independent of area. This indicates a diffusivity of about 60 km^2 s^{-1} for the smaller active regions. It may be worth noting that this constant decay rate law extends up to spots with sizes of about 200 μHem which is also about the size of a typical supergranule. This in turn suggests that the decay of these small spots is dominated by the diffusive effects of smaller turbulent eddies, i.e. granulation modified by magnetic fields.

The larger regions decay at rates that increase with region size. This gives region decay with some fractional area disappearing every day. The slopes we find give a fractional loss of about 8% day^{-1}. This is significantly less than the 25% day^{-1} found by Howard (1992b) but can be reconciled by the fact that his value represents the median value for all regions. Since about half of the regions are the smaller ones with constant (and fractionally larger) decay rates, they tend to dominate Howards median measurement. Howard's measurements of the decay rate as a function of area does not, however, show the constant value we find here. He finds a decay rate that increases from 0 to 50 μHem day^{-1} as the region area increases from 5 to 150 μHem. Our two studies differ in some respects (Mt. Wilson vs. RGO data, 2-day vs. 3-day intervals, bin size, and data selection) but it remains difficult to understand this difference in these results. Another significant aspect of Howard's study is his finding that the fractional growth rates increase with latitude. This is confirmed in our own study and largely explains the observed difference in decay rate between rising and falling phases of the sunspot cycles.

Moreno-Insertis & Vázquez (1988) studied active region decay using the RGO data from 1874 to 1939. They tested different functional forms for the decay phase by fitting an exponential, a quadratic, and a linear decrease in area with time for the disk passage of decaying active regions. They too limited the data to observations within 60 of the central meridian and to spots with areas > 35 μHem. In addition they limited their analysis to those regions with 5 or more daily observations within these limits. They found an average decay rate for all groups of about 27.8 μHem day^{-1} which agrees with our results given the distribution of group sizes (Fig. 6). They found that an exponential fit was better than a linear fit for only about 5% of the regions. We find that about half of our measurements (regions with areas > 200 μHem) give a decay rate proportional to area which should give a decay that is exponential in time while the regions remain large. However, the decay rates are still small enough for most regions to give what appears as a linear decay over the few days they are observed. Moreno-Insertis & Vásquez also indicate that most regions had decay rates that were best represented by a quadratic in which the quadratic term dominates the linear term. This would give a decay rate proportional to the square root of the area a result that is at odds with our own analysis. Note, however, that finding a quadratic fit and comparing the linear term to the quadratic term in a non-dimensionalized equation is not the same as comparing the goodness of fit between functions that vary as time squared to those linear in time.

Martínez Pillet, Moreno-Insertis, & Vázquez (1993) measured active region decay rates using the RGO data from 1874 to 1976 and concluded that the decay rates are distributed log-normally and that this distribution varies from cycle to cycle. The first result is consistent with our own analysis. While we find a basically linear relationship between decay rate and region area, we also find that the region areas are log-normally distributed. This is shown in Fig. 6. While we agree on the shape of the distribution we differ on the solar cycle variability. Here we find no significant variations in the decay rate law from cycle-to-cycle. The variations they see in the distribution from cycle-to-cycle could be attributed to variations in the distribution of active region areas. Their analysis also suggests a preference for a quadratic time dependence.

Petrovay & van Driel-Gesztelyi (1997) analyzed data from the Debrecen Photoheliographic Results for 1977 and 1978. They also find evidence for a quadratic time dependence that would indicate a decay rate that varies like the square root of the region area. However, the small dataset and significant scatter in results do not exclude a decay law like that found here.

Recently, Chapman et al. (2003) examined the decay of 32 sunspots observed with the Cartesian Full Disk Telescope at the San Fernando Observatory. Although this is a small sample, the individual measurements are quite accurate. They find a linear relationship between decay rate and area with virtually the same slope as ours (0.084 ± 0.0093 vs. our 0.079 ± 0.0025) but do not find the constant decay rate regime for small regions. (Note that the diffusion coefficients, η, that they derive are direct conversions from decay rate, Γ, without the factor of 4π indicated in Eq. 5 for Fickian diffusion. Including this factor reduces the diffusivities by more than an order of magnitude.)

While we find that the decay rates for active regions increase linearly with region area for regions larger than about 200 μHem, this does not exclude the possibility that the decay of these larger regions is produced by erosion at the perimeters of the spots. Large regions usually consist of a large number of spots and spots with complex boundaries. The length of the spot perimeters within such group will increase faster than the square-root of the area and may in fact increase more like the area itself. The somewhat smaller than expected (from the linear relationship) decay rates for the largest groups in our study may be an indication that the decay of the larger regions is by boundary erosion from complex (fractal) boundaries.

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REFERENCES

Bumba, V., 1963, Bull. Astron. Inst. Czech., 14, 91

Chapman, G. A., Dobias, J. J., Preminger, D. G., Walton, S. R., 2003, Geophys. Res. Lett., 30, 27

Cowling, T. G., 1947, MNRAS, 106, 218

Fan, Y., Fisher, G.H., & DeLuca, E.E. 1993, ApJ, 405, 390

Fan, Y., Fisher, G.H., & McClymont, A. N., 1994, ApJ, 436, 907

Howard, R. F., 1992a, Sol. Phys., 142, 47

Howard, R. F., 1992b, Sol. Phys., 137, 51

Kálmán, B., 2001, A&A, 371, 731

Krause, F., and Rüdiger, G., 1975, Sol. Phys., 42, 107

Martínez Pillet, V., Moreno-Insertis, F., and Vázquez, M., 1990, Ap. Space Sci., 170, 3

Martínez Pillet, V., Moreno-Insertis, F., and Vázquez, M., 1993, A&A, 274, 521

Martínez Pillet, V., 2002, Astron. Nachr., 323, 342

Meyer, F., Schmidt, H. U., Weiss, N. O., 1977, MNRAS, 179, 741.

Moreno-Insertis, F. and Vázquez, M., 1988, A&A, 205, 289

Parker, E. N., 1975, Sol. Phys., 40, 291

Petrovay, K., and van Driel-Gesztelyi, L. 1997, Sol. Phys., **176**, 249.

Stix, M., 2002, Astron. Nachr., 323, 178

Thomas, J. H., et al., 2002, Nature, 420, 390

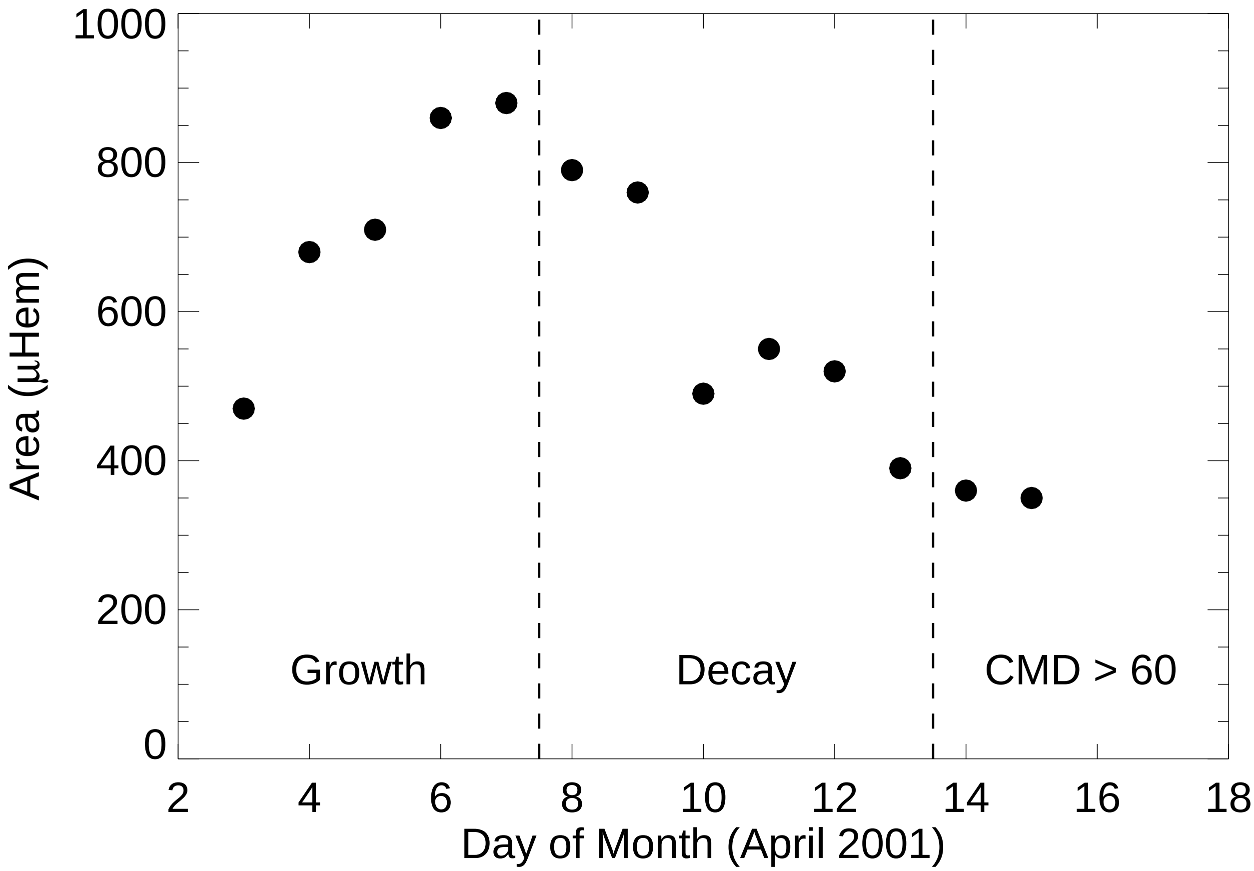

Fig. 1.— Sunspot area measurements for NOAA AR 9415. The filled circles represent the daily measurements of the sunspot group area corrected for projection effects. The vertical dashed lines set-off the different segments (growth, decay, and CMD $> 60^{\circ}$) of the active region history. Our selection criteria yield four measurements of the decay rate for this active region for four different values of its area.

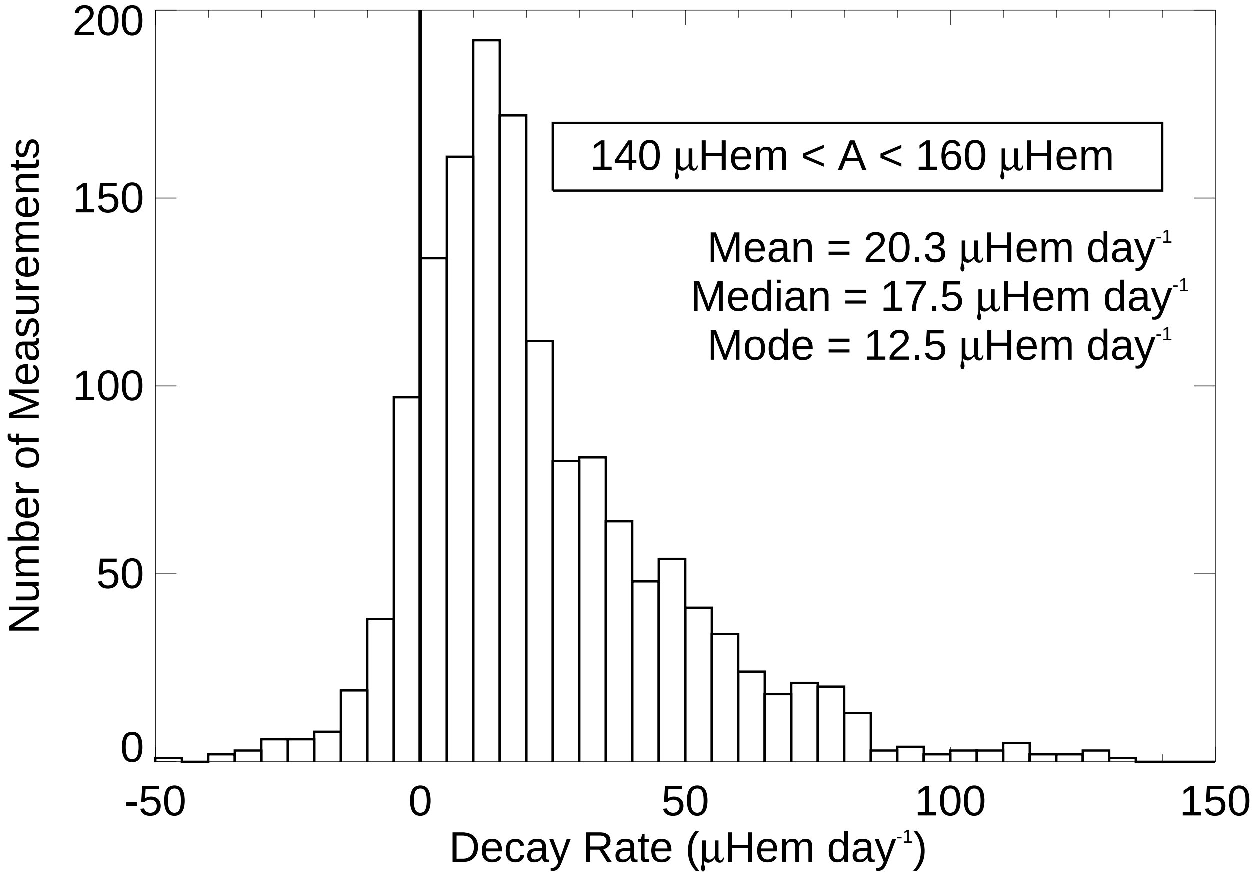

Fig. 2.— Histogram of the number of measurements of decay rates between -50 and +150 μHem day^{-1} for active regions that had measured areas between 140 and 160 μHem. The distribution is skewed toward higher decay rates but gives similar values to both the mean and the median.

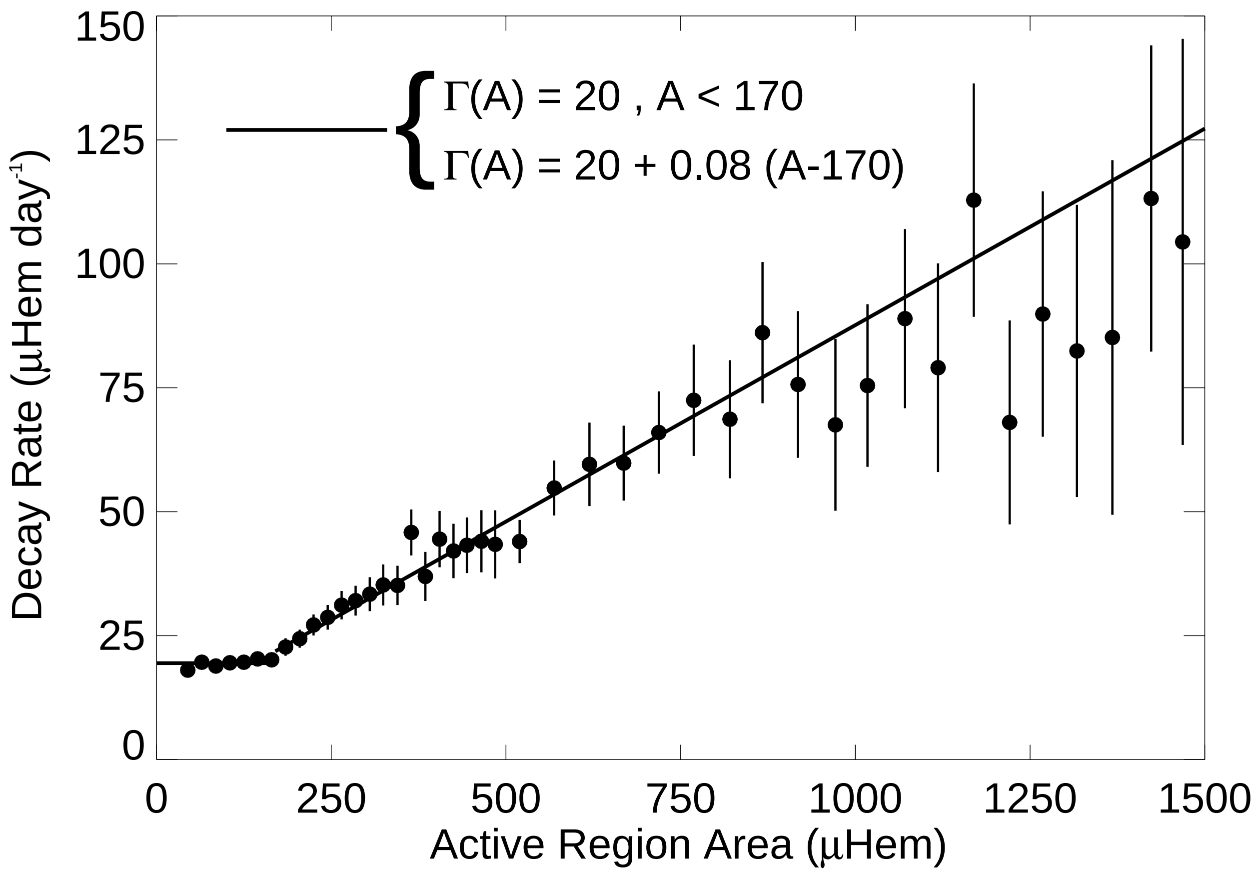

Fig. 3.— The decay rate of active region area as a function of area itself. Regions with areas less than 200 μHem decay at a rate of about 20 μHem day^{-1} that is independent of region area. Larger regions have decay rates that increase linearly with their areas. The largest regions ($>$ 1000 μHem) have decay rates that fall somewhat below this linear relationship.

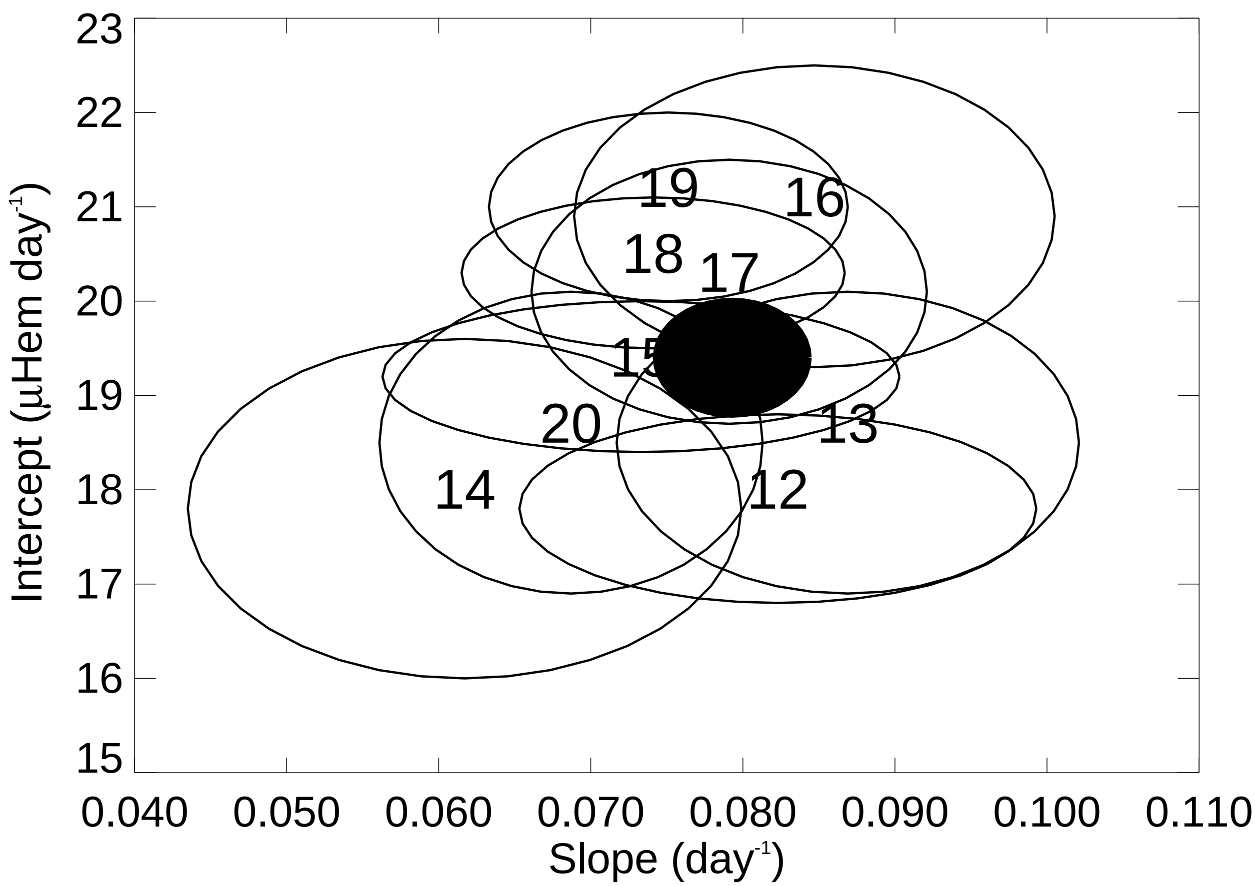

Fig. 4.— Active region decay rate error ellipses for sunspot cycles 12-20. The small spot decay rate is given by the Intercept and the rate of increase in the decay rate with area is given by the slope. Each sunspot cycle number is plotted in the center of its ellipse and the error ellipse for the full data set is shown with the filled ellipse. Active region decay rates show no significant variations from cycle to cycle.

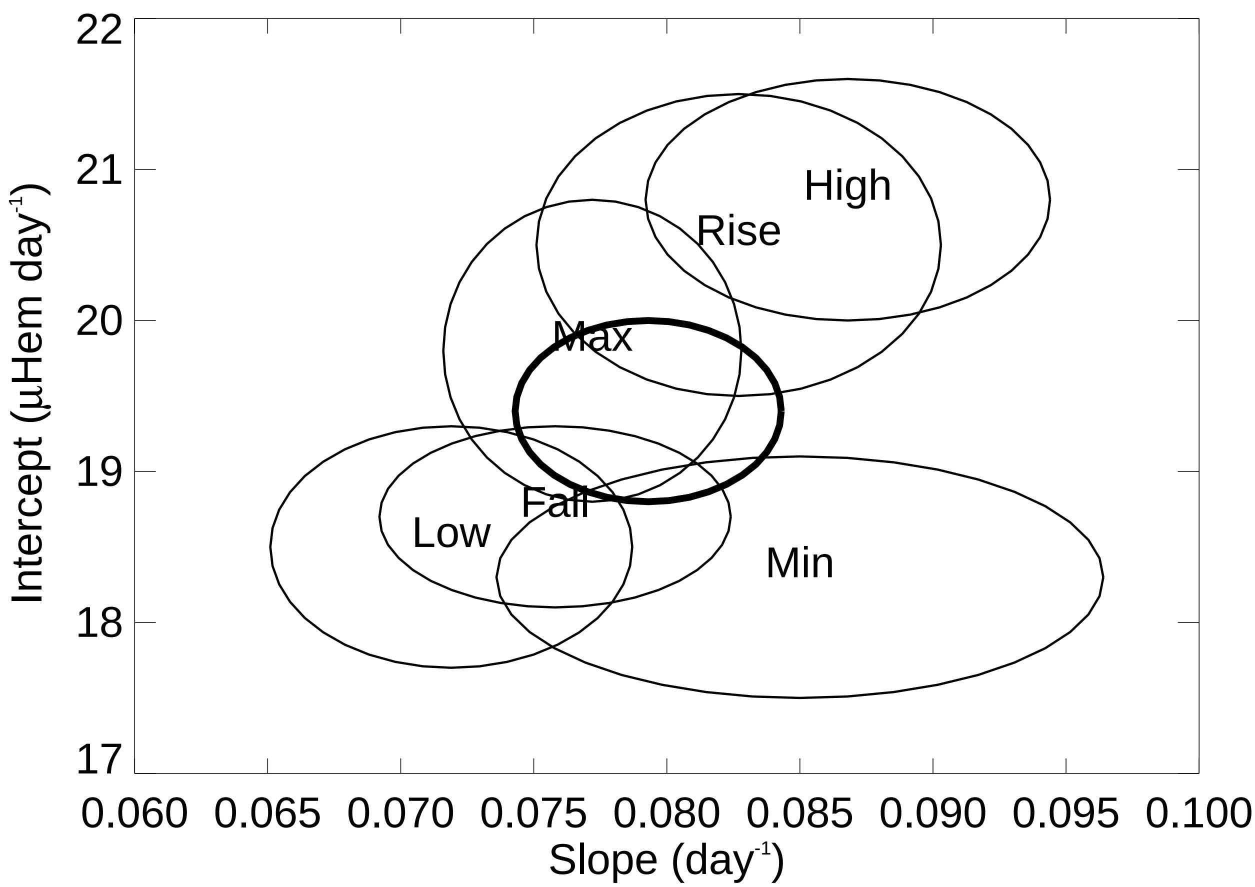

Fig. 5.— Active region decay rate error ellipses for different phases of the sunspot cycle and different latitudes. Each ellipse is labeled with its corresponding phase of the solar cycle. The thick ellipse in the center is for the full dataset. Active region decay rates vary with latitude with slower rates at lower latitudes.

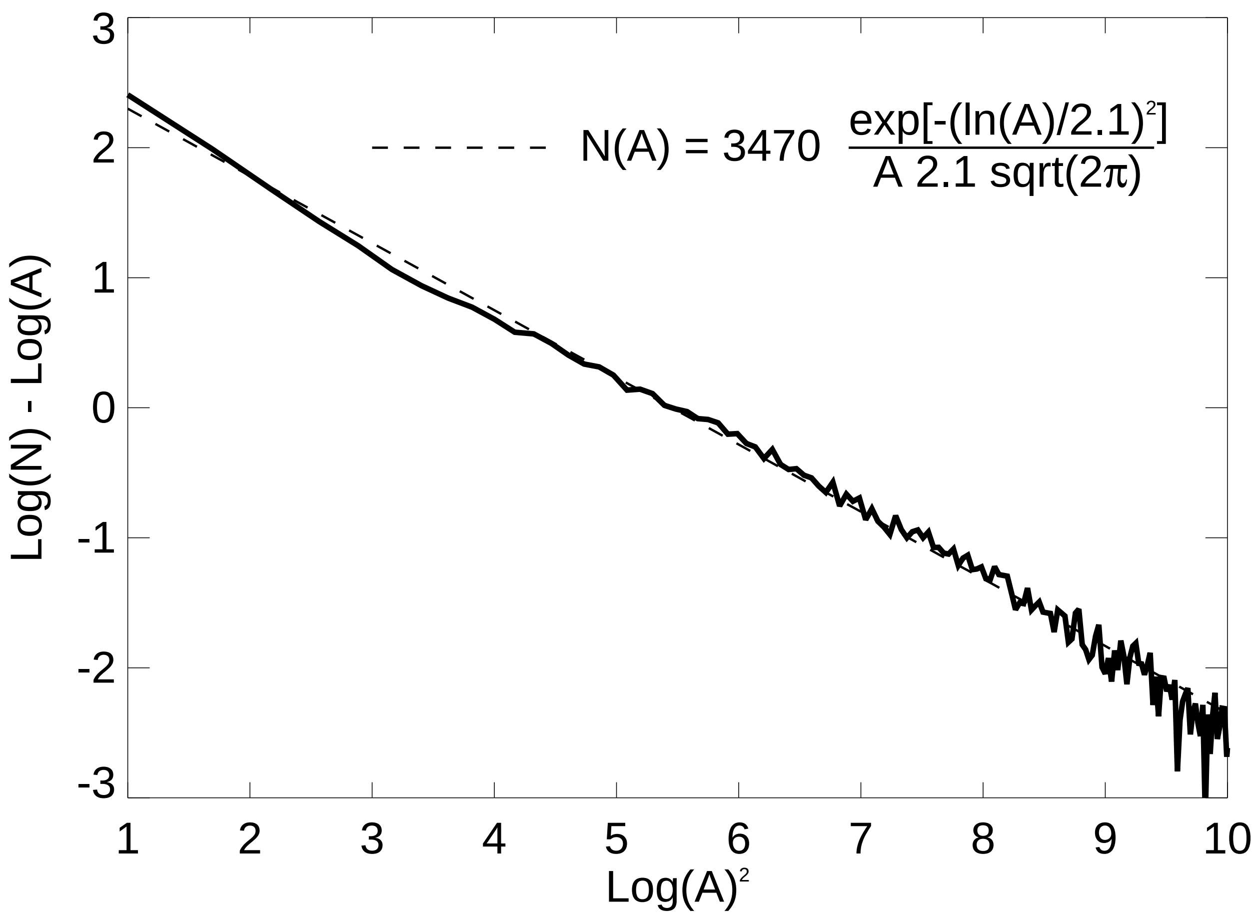

Fig. 6.— Active region size distribution. The number of active regions of a given maximum size A is plotted as a function of size for the full dataset. The distribution is well represented by a log-normal distribution (dashed line and inset equation).